UNCERTAINTIES IN MEASUREMENT AND ESTIMATION AND THEIR EFFECTS IN COMMUNITY NOISE

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1 INTRODUCTION

There are two uses that are very much affected by uncertainty in measurement: a) the determination of sound power (by measurement or by algorithm) to estimate sound immission based on algorithms and b) the measurement of noise to compare with community noise regulations. Uncertainties in the first case result in compounded uncertainties in the second case and without attention to these, the results will be unhappy citizens.

Noise measurement is based on imprecise instruments. Noise estimation is based on algorithms that are subject to experimental error. Errors in measurement and errors in estimation can be in the two digit decibel range easily.

We often make measurements with no concern for their accuracy. We assume we measure what is produced. Similarly, we estimate sound levels at a distance with many implicit assumptions. This paper discusses some of the potential uncertainties that arise and their effects. It is meant as a collection of discussion topics and to make the reader aware of the issues involved.

2 ORIGINS OF UNCERTAINTIES

2.1 Measuring sound pressure

Hydrostatic pressure is a point characteristic, a scalar with magnitude only and no direction. For atmospheric pressure, the pressure at two closely spaced points is essentially identical and the sound pressure that hits the points at any given time is a function of wavelength which is generated by the frequency of the source (and the speed of sound.) Since the sound pressure level is determined from some time-averaging process, over any small distance the sound pressure level variation is very small. However, that dynamic pressure, a time dependent signal which implies a frequency dependent signal, is indirectly detected by a microphone. Actually, the dynamic pressure hits a compliant object (usually a circular diaphragm) that mores in response to pressure. This motion is detected as a change in voltage and a supposedly linear relationship between pressure and displacement and between voltage and pressure is assumed for modern microphones.

Microphone characteristics

Frequency response: The linear relationship between pressure and voltage is assumed over some frequency range for a given microphone orientation. However, this range varies with microphone. Figure 1and Figure 2 shows two microphones responses from two different microphones, for a Class 1 system and a Class 2 system, respectively. Note for the Class 2 there is no information given for a range greater than 10,000 Hz. But between 10,000 and 20,000 hertz, and even higher, there may be sounds produced. Above 20,000 Hz the effect of sounds on the measurement is unknown for both "types" and above 10,000 Hz there is a good chance one microphone will perform differently than the other. Even in the overlapping range, depending on the spectrum of sound measured, results can be off by 1 dB.

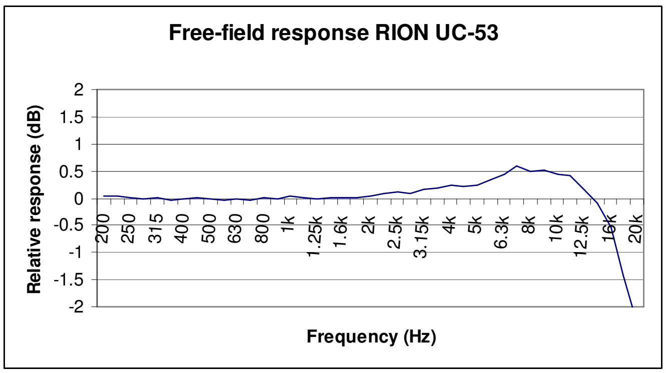

Figure 1 Class 1 microphone RION UC-52

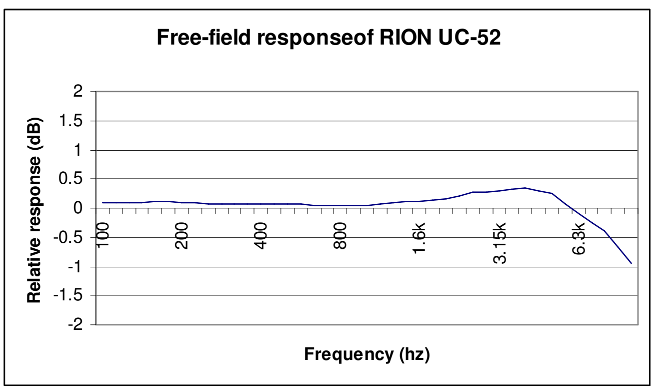

Figure 2 Class 2 microphone RION UC-52

Free-field or pressure response: Omnidirectional microphones are those that, in general, have a frequency response that is symmetric over any circumference perpendicular to the diaphragm axis. And the microphone frequency response is fixed for a given orientation. Usually the microphone frequency response is well known for normal incidence sounds: perpendicular to the microphone, and often it may be known for grazing incidence sounds, and even some other angles. For a given physical construction, the relationship between these different responses can be quantified and made part of the microphone documentation.

When calibrated by normal and affordable means, the microphones are subjected to an equivalent uniform pressure over the diaphragm. And, based on construction and grid characteristics, and previously measured data, both random incidence[1] and free-field responses can be derived.

But the actual measurement is rarely measured in an ideal field. Even in an anechoic field, often the source is not a point source and the sound is not normal to the diaphragm. And, in general, the characteristics of the measurement field are not known. This applies for emission (sound produced) and immission (sound received.) So the frequency response characterized by the microphone calibration laboratory is not that of the measurement.

Depending on frequency, a microphone is not omnidirectional with respect to a diameter of the diaphragm. Sound coming from the rear, depending on the frequency can be easily attenuated by 10 dB or more. So that, if you use a free-field microphone, pointed at, say a lane of traffic, the sounds behind that microphone, if of significant level, will influence the reading by some unknown way. (See Figure 3, Figure 4, and Figure 5)

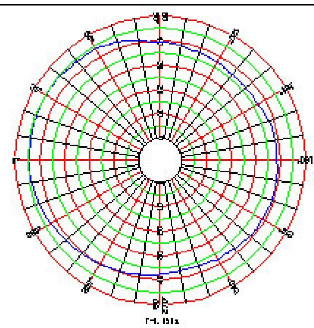

Figure 3 Response at 2.5 kHz

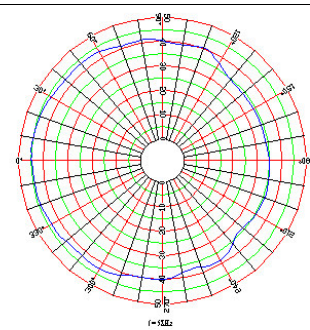

Figure 4 Response at 5.0 kHz

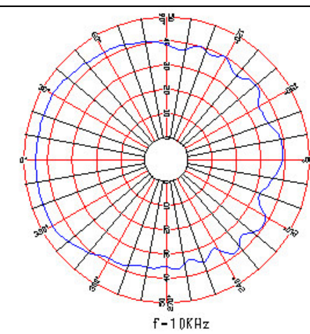

Figure 5 Response at 10 kHz

Windscreens: The insertion loss (IL) of a windscreen, excluding the effects of wind generated noise, is frequency dependent. Not all windscreens have similar insertion losses (Figure 6). Size, porosity, material, fit with the microphone/preamplifier combination, and moisture, all contribute to the insertion loss. And many of these characteristics vary with batch or installation. For an arbitrarily chosen windscreen, the insertion loss can vary significantly. Figure 7 shows the IL for two 'all-weather' windscreens. The IL above 3 kHz is rather high. The problem is, unless either there is little high-frequency sound to measure, or the insertion loss is known, one cannot tell what the windscreen does to the measured sound, by spectrum or even by A-weighted measures.

[1] Random incidence response is an average response determined by integrating the sound when the microphone is subject to the same sound level coming from random directions at different times. Diffuse field response is the response due to sound coming from all directions simultaneously. These are conceptually different and produce slightly different responses.

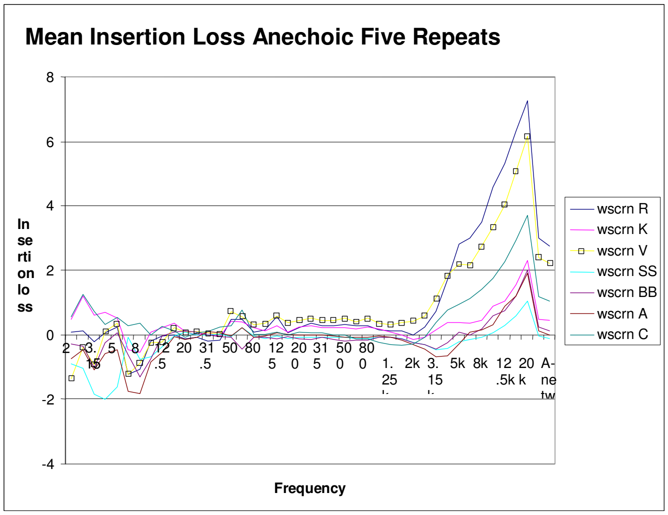

Figure 6 Examples of windscreen insertion loss

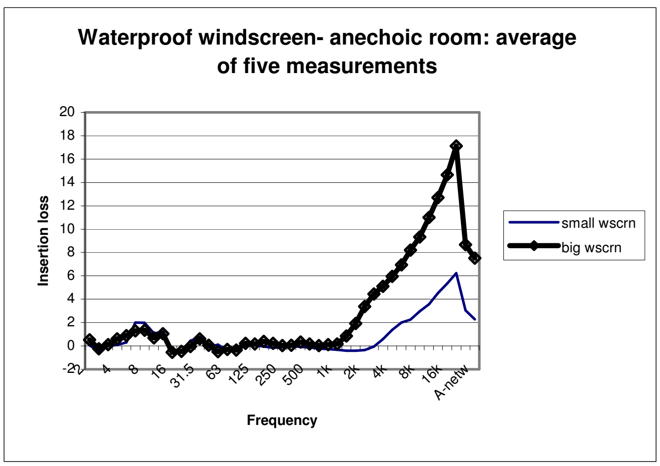

Figure 7 "All weather" windscreens

In general, the characteristics of a windscreen are not known. While we can characterize them, few persons are willing to pay for the data. Further, the insertion loss varies with batch and the differences are very windscreen-dependent. Few manufacturers provide frequency responses for their windscreens. As a result, the signal coming into the meter to be further analyzed is often changed by what is in front, in an unknown way.

2.2 Converting sound pressure to sound pressure level

Sound level meter characteristics

Microphones are attached to meters and the combination is called a sound level meter. The frequency response, linearity, time response, averaging approaches, filter characteristics, etc., are all governed by standards to which they are supposed to meet. These standards are from well known standards writing organizations: International Electrotechnical Commission (IEC) and American National Standards Institute (ANSI), are among the best known. We often assume these are met by the instrument we use but often they can only be tested in a limited way[2]. Further, acoustical calibration laboratories are not regulated although some may be accredited. So, there are no national regulations (in the USA anyway) that assure calibration laboratories are calibrating correctly. So the calibration certificate really does not guarantee anything about the performance of a meter. Accreditation is, at present, the only assurance of credibility.

Calibration

Folk stories say it pays to calibrate before and after every measurement. Of course this is not a calibration, rather it is a simple sensitivity check at one frequency. It involves putting an acoustical calibrator on the meter and confirming, or adjusting the sensitivity to meet the calibrator level. Rarely is a calibrator's output exactly what is listed on the label. But that value is often used as the reference level for sensitivity. Some calibrators have multi frequency capability but there are no directions on how to adjust sensitivity for more than one frequency. At any rate, the calibrator error is part of the uncertainty in the measurement for emission AND immission.

Calibrators come in two classes of accuracy based on ANSI and IEC standards. Class 1 is ±0.3 and Class 2 is ±0.5 So, adjusting the sensitivity using a "calibrated" calibrator can add uncertainty.

2.3 Determining sound power

To make any estimation of sound immission one must know the sound power level of the source. Often the common sound power standards from ANSI and International Organization for Standardization (ISO) are cited. Most deal with small sources: fans, electrical generators, snow blowers, heat pumps, etc: These can be tested in laboratory environments. Bigger, well-defined sources like cooling towers, can be tested in the field in a controlled area. But many sources cannot. These include rock crushers, turbine exhaust stacks, and large ID or FD fans. They are either too large to test in the laboratory or in a controlled area, or have appurtenances that also make noise and are impossible, for geometrical reasons, to test accurately. But accurate sound power level and directivity are essential for further noise estimation. Uncertainties in power propagate to uncertainties in pressure at a distance. These power level uncertainties come from several effects, besides the measuring instruments.

Environment

For large sources, outdoors, sound power is inferred from sound pressure (or sound intensity) at a distance. If you can isolate a source, measure the sound pressure, the sound power is known, based on some assumptions. In the field, often, to approximate a point source, you need to be at some distance from the source and the straight line distance can be hard to measure accurately. If you are off by 10% (say 20 m in a 200 m measurement, your uncertainty is about 1 dB. So the distances used for measurement of sound pressure from large sources should be accurately measured. Clearly, if there is an error in sound power, then there will be a comparable error in sound pressure at a distance.

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[2] For example, meters without removable microphones can only be checked at discrete frequencies with acoustical excitation. So the accuracy is less and number of functions tested to comply with standards is fewer.

For small sources (often not loud enough to matter in the community) and for some large sources like dozers (which really affect the environment) sound power is determined in anechoic rooms. These rooms often are qualified, to assure a "free-field" environment, in accordance with ANSI and ISO standards. This qualification approach to the room places a small (point) source in the center or at the test area and checks to see a 6 dB per doubling of distance over some area around the source. Where this 6 dB doubling occurs is a free and far field area and the area in which measurements of sound pressure can be made. For small sources this approach is adequate and gives an expected standard deviation of about 1.0 to 1.5 dB (yielding an uncertainty of 2.0 to 3.0 dB, depending on frequency).

There is a rather large uncertainty allowed in the anechoic field (Figure 8) which contributes to the measurement uncertainty. But the uncertainty assumed is based on a small stable source in this almost "free-field."

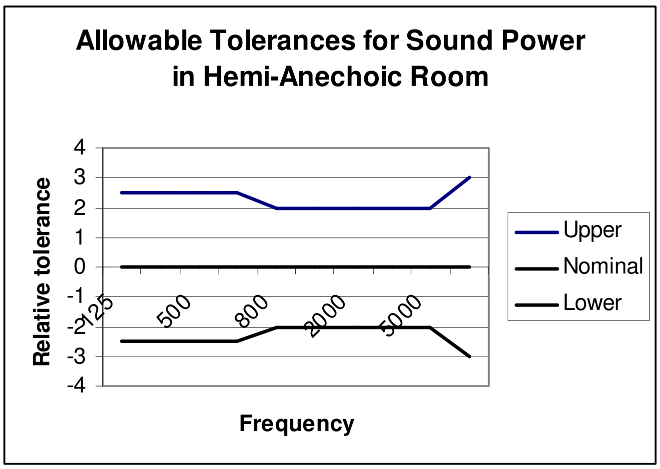

Figure 8 Allowable deviations from theoretical decay from ISO 3745-1977

However, if the source is large, there is no point source and there are multiple reflecting surfaces on the source. So free field, or even far field, conditions may not be approached. So the reported uncertainty from the standard may not indeed be related to the uncertainty measured.

Source characteristics

Many sources have complex geometry and complex operating modes: from a stationary air conditioner that cycle on or off to a grader that moves, has sound emission that is a function of load and operating mode. Thus the source itself produces sufficient variability to make measurements more than slightly uncertain. A classic example is the sound power of a dozer. For the same brake HP (kW) of several brands of dozers, the sound power can be significantly different for the simple case of a stationary operating position.

A source can translate, like a vehicle, or rotate, like a grader, or do both, like a loader. Several standards purport to measure, maximum pass-by levels, or average A-weighted sound level around the equipment, but I don't think any measure with a load. Thus the sound power determined from these pressure measurements has significant uncertainty. A 10 dB difference in Idle-Max-Idle (IMI) measurements and loaded measurements is common. Further, if the source is moving the directivity and the distance can vary significantly with time. This leads to another issue, discussed later: what is the right length of time or metric to measure. Work cycles per Society of Automotive Engineers standards (e.g. SAE-J88) are meant to categorize the source in some standard way. The disparity between the standard work cycle and a real work cycle, which may cover an area of 800 m^2 is sufficient to put little value in data obtained for these tests when using it for determination of immission.

If a source has tonal emissions they create interference and reinforcement and are often highly directional and more annoying than the A-weighted sound levels might suggest. If there is a directional component to the sound, then often the reverberation room method, or even a free-field method, may miss this characteristic.

The temporal nature of sources can be a very big issue. Traffic is an example. Measuring on a "typical weekday" may, in fact not be representative at all if there is no typical day. And the only way to know if one day is representative of another is to measure all of them and chose those that are representative. Traffic volume may be an indicator, but only of the traffic volume of the day is the same as many other days. Even so, the speed, truck mix, etc., may be sufficiently different to have a measured value different than what is needed.

If a source operation is cyclical, like an HVAC unit, then the metric for maximum, or average, may be representative or conservative, or too liberal description of the condition needed.

2.4 Uncertainty in propagation effects

The uncertainty in sound power determination will be exactly the uncertainty in sound pressure estimation if the predictions are done with no additional added uncertainty. Following are some issues in the propagation model.

Algorithms

An algorithm in this context is an equation that relates sound pressure at a point to sound power produced by the source. In theory, and perhaps only in theory, the simplest equation is for propagation in a free field by a point source, where:

$$Lp=Lw-10*\log_{10}(\text{distance})^2 + \text{Constant}$$

If plotted as sound pressure level v. log (distance), it is a straight line. Even in a hemi-anechoic room, there is allowable deviation from this theoretical equation. (Figure 8) So, this simple formula, above with nothing complicating it, yields a practical uncertainty.

In general, the basic frequency dependent formula for propagation is a linear combination of the basic equation, above and some complex terms:

$$Lp = Lw-20*\log_{10}(\text{distance}) + \text{Constant} + \text{Attenuation}$$

Where the Attenuation is a frequency dependent set of numbers that is derived from equations and covers several factors: ground effects, atmospheric absorption, thermal gradients, buildings, barriers or berms, wind, and foliage. Each of these attenuation terms are algorithms based on experimental or theoretical data and each contributes it own uncertainty. But infrequently are the ranges of uncertainty included.

Algorithms are based on experimental data and can be quite complex. An abstract by Finette, for underwater acoustics, expresses the real complexity of algorithms[3].

Weather (precipitation, wind, temperature gradients, temperature)

Measuring in rain or snow is usually not a good idea, but is always done in permanently mounted outdoor monitors. The effects of rain on source emissions are mostly due to different tire/road noise on vehicles. I have seen no studies of the attenuation of precipitation. Probably the sound of rain, at least, increases the measured sound level as it hits the microphone protection grid. Frozen windscreens can cause significant change in measured frequency response often unknown to the operator[4].

Wind at a point is temporally variable in speed, direction, and elevation. Air temperature is more static and varies, usually slowly, as a function of elevation. But the temperature also mildly depends on nearby thermal radiation and other heat sources or sinks(like bodies of water) and the effect of winds on the moisture in the air. There have been many theoretical studies to calculate uncertainty if wind velocity and temperature gradients are known. According to ISO 1996-2, the estimates in standard deviation vary from about 1.5 dB to 2.0 dB.

Practically, the situation is much worse. When in the field it is virtually impossible to measure gradients of temperature or wind, either instantaneously or for long term averages. Most often, the temperature and wind at the surface (perhaps 1.5m above the ground) are known and recorded. So the equations cannot be applied accurately. Two other major factors must be included: a) the effects of the wind on the measurement, b) the metric used. LmaxF will be different, and much more variable than LmaxS or than Leq(1-hr).

Distance

Distance is discussed above as it pertains to measuring for determination of sound power. The uncertainty in distance in measuring or predicting immission is much less important than for the determination of source emission because the error, especially at large

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[3] Finette writes, "A probabilistic formalism is proposed for the direct inclusion of environmental uncertainty into an acoustic model that describes propagation in an ocean waveguide. Incomplete environmental knowledge is characterized by a spectral representation of uncertainty using expansions of random processes in terms of orthogonal random polynomials. A brief summary of the method is presented and a set of coupled differential equations describing the propagation of both the acoustic field and its associated uncertainty is derived for the case where the uncertain environment is attributed to a lack of complete information concerning the waveguide's sound speed distribution."

[4] One windscreen, the RION WS-04 actually prevents any freezing, using a heater-blower system to keep the screen clear, and is good to a claimed -15ºC.

distances, is very small. But an uncertainty in sound power can give very large uncertainties in estimated sound pressure level at far distances.

Foliage and Ground effects

There are at least two issues about foliage and ground effects that contribute to uncertainty: a) the database on attenuation is sparse and contains widely varying values of attenuation[5], and b) actual measured data, in the field, is hard to determine. For examples:

- What is the density and geometry of the trees compared to published data?
- Is the density homogenous?
- What if the ground consists of mixed properties in varied areas between source and receiver? (e.g.: asphalt, ground, grass, asphalt)
- How do you know the properties of the ground at the specific site?
- ISO 9613-2 provides guidance for simple, flat, hard ground. The difference between their assumptions and the conditions at the actual site contribute to additional uncertainty.

Barriers

Barrier attenuations are based on theoretical calculations. Complex barriers, like double walls, thick walls, or berms, are approximated, usually, from perturbations of the thin, infinite, barrier equations. Often, sloped barriers, uneven berms with ground cover, slots, etc. will yield undetermined uncertainties from predictions.

2.5 Duration and sampling of the measurement

The duration of the measurement must be sufficient to characterize the source. For statistical significance, a certain number of cycles (or pass-bys) must occur: the number proportional to the accuracy. For example, the uncertainty in Leq as a function of single type of vehicle pass-bys is $10/\sqrt{n}$ per ISO 1996-2. But this number is different for each metric, and for each traffic mix, since the maximum Lp, at least, is vehicle type dependent.

If you need to characterize a site over a lengthy time period it is best to measure over that period. Engineering judgment is needed then to extrapolate that to another time period. However, if the sampling period is limited and must estimate or characterize the noise at location, or even at an area, the sampling approach must be well thought out. And the method of sampling is very dependent on the metric. ISO 1996-2 recommends that any measurement time exceed at least three cycles[6]. If a continuous measurement is not possible, samples within these three cycles must be representative.

2.6 Measuring sound pressure

The uncertainties in measuring sound pressure level for immission is similar to that measuring for emission. Uncertainties should be included for the measurement. Often, in the USA anyway, the allowable criteria are based on indoor noise levels. The

[5] For example, Beranek shows values that vary by 7 dB/100 m
[6] This implies if a daily average is required, a measurement of at least three days is needed.

specification may read something like this: "the development can proceed as long as the indoor Ldn is less than 45 dBA." The difficulties of measuring indoors, the lack of specificity of measurement method, the impossibility of checking the measurement, the effects of noise from the inhabitants, and many other issues makes any similarity between estimated and measured levels in these situations purely coincidental.

2.7 Uncertainty issues with metrics

The metric is a very large contributor to the overall uncertainty. As the measuring time increases, the fluctuation in the metric reduces. Sometimes the metric is prescribed and the measuring time (interval) is specified. But if not, the following must be considered.

Leq

This depends a great deal on the sources. If there is an infrequently occurring cyclical sound, such as low density traffic, the Leq can vary depending on when the measurement is made. If traffic volume is low the exposure level (LE) can be measured and extrapolated for multiple events. ISO 1996-2 recommends about 10 minutes measurement to obtain an average. But, an average over a few minutes may not be representative of the worst case because traffic mix may not be such to have the nosiest vehicles contributing.

MAX or Peak

Using the maximum implies a time constant and, of course, the value measured will be different[7], depending on that time constant. (For the same sound produced, the reading will be different, depending on FAST or SLOW.) Clearly, the MAX reading will vary considerably depending on the time for the measurements. Peak readings, rarely used in community noise ordinances, except when confused with Max, are even a greater variability. For a controlled sound (in a laboratory) the peak sound levels for the same signal can vary from about 1.5 to 3.5, depending on type of meter and frequency (See IEC 61672). So the measurement error added to the variability caused by sampling is reason enough not to use peak.

Ldn

The Ldn is a relatively stable descriptor. First it takes a long average yearly (?) or 24 hours. Secondly it contaminates the nighttime average by a 10 dB higher average that gets added to the daytime, reducing wide discrepancies in range. Of course one pays for the stability with lack of detail and lack of information that can cause community complaints.

2.8 Microphone location

The microphone location is often prescribed by the measurement procedure attached to a community ordinance. But here are some things to consider:

- The larger the distance between the source and the microphone, the less important the location.

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[7] Using F will correspond more to human response and S will be more reproducible.

- The orientation of the microphone can have a profound effect, depending on frequency of the source.
- The Type 1 and Type 2 meters should give significantly different results for a high frequency source[8].
- Avoiding reflecting surfaces is the norm in most measurements . But if one is trying to measure immission then sounds in a reflecting area should count.

3 RAMIFICATIONS AND CONCLUSIONS

The ramifications of uncertainty in measurements are twofold.

1- If you know the uncertainty you can determine the effects of the measurement. In ISO 1996-2 they state the uncertainty of reproducibility is 1 dB. Other uncertainties, due to operations, to weather, and to ambient (they call residual) sound, can be combined. If we are very liberal, and assume only a 1.0 dB uncertainty for some of the unknowns, then the combined uncertainty is 2.0 dB and the expanded uncertainty (a 95% confidence that the measurements will lie in the range) is ± 4.0 dB. This is probably very optimistic yet an expanded uncertainty of 4 dB is significant and should be accounted for in developing and enforcing municipal noise ordinances.

2- If you don't know the uncertainties, which is often the case, and can't estimate them you don't know anything about your measurement.

So it is critical that all measurement uncertainties be known or estimated and accounted for. All reports should state a confidence interval to inform all readers of the uncertainty in the measurements.

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Finette, Steven, "Embedding uncertainty into ocean acoustic propagation models," Acou. Soc. Of Amer., v117, No.3, Pt 1 of 2, March 2005, pp.997-1001

[8] In our experience, for automobile sources, the difference between reading s of A-weighted sound level of a calibrated Type 1 and Type 2 is less than 0.5 dB